

Observing Baryon Oscillations with Cosmic Shear

Fergus Simpson*

Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA

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A cosmic shear survey, spanning a significant proportion of the sky, should greatly improve constraints on a number of cosmological parameters. It also provides a unique opportunity to examine the matter power spectrum directly. However, the observed lensing signal corresponds to a weighted average of the power spectrum across a range of scales, and so the potential to resolve the baryon oscillations has been somewhat neglected. These features originated prior to recombination, induced by the acoustics of the photon-baryon fluid. Recent galaxy surveys have detected the imprints [1, 2], and in the future such measurements may even be used to refine our understanding of dark energy.

Without redshift information, cosmic shear is an ineffective probe of the baryon oscillations. However, by implementing a novel *multipole-dependent* selection of photometric redshift bins, sensitivity is improved by an order of magnitude, bringing the “wiggles” within reach of future surveys. As an illustration, we show that data from surveys scheduled within the next ten years will be able to distinguish a smoothed power spectrum at the 2σ level.

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I. INTRODUCTION

Consider the observation of a pair of distant galaxies. Their images accumulate a correlated distortion as the light is gravitationally deflected throughout the multi-billion year journey, thereby generating an illusion of alignment. The extent of this lensing signal, known as cosmic shear, is related to the magnitude of density perturbations lying between the two paths. Thus as their routes gradually converge, the sensitivity to the matter power spectrum traces an ever-decreasing distance scale. Since the power spectrum is probed over such a broad range, it was not anticipated that cosmic shear surveys could resolve any oscillatory features.

However, the cosmic shear technique offers much promise, with ambitious surveys planned which far surpass those that have been conducted to date. These will push various cosmological parameters to sub-percent levels of precision, provided systematic effects can be sufficiently controlled. It also presents the most direct probe of the matter power spectrum, and recently particular emphasis has been placed on constraining the dark energy equation of state w [3, 4, 5, 6].

In this work we aim to show how the presence of baryon oscillations can be inferred from cosmic shear data, acting as an auxiliary probe to galaxy redshift surveys. The importance of independent evidence cannot be underestimated, as it is essential if we are to claim a concordant model. A successful detection will also build confidence in the validity of other parameters.

Central to our approach is the concept of dividing the galaxies into different redshift bins when analysing different angular separations. This allows us to compare the shear signal which is suppressed by the wiggles, with

those which are enhanced.

In §II we briefly review the theory of cosmic shear, and outline the fiducial survey. §III then determines the redshift bins we will use to reveal the baryon oscillations, using the optimised statistic defined in §IV. The errors associated with this statistic are derived in §V.

II. THE FIDUCIAL COSMIC SHEAR SURVEY

For our purposes, there are two important inputs which determine the form of the cosmic shear signal - the matter power spectrum, and the distribution of source galaxies. Essentially, we will look to optimally probe the former, by manipulating the latter. The cosmic shear power spectrum is given by

$$C_\ell = \frac{9}{16} \left(\frac{H_0}{c} \right)^4 \Omega_m^2 \int \left[\frac{g(\chi)}{ar(\chi)} \right]^2 P\left(\frac{\ell}{r}, \chi\right) d\chi, \quad (1)$$

where χ is the coordinate distance, and $r(\chi)$ the comoving angular diameter distance. The galaxy distribution $n(\chi)$ features within the lensing efficiency g , given by

$$g(\chi) = 2 \int_\chi^{\chi_h} n(\chi') \frac{r(\chi)r(\chi' - \chi)}{r(\chi')} d\chi', \quad (2)$$

where

$$n(z) \propto z^\alpha e^{-(z/z_0)^\beta}. \quad (3)$$

The constants α , β , and z_0 are taken from Refregier et al. [5]. We will assume a flat universe throughout, and hence $r(\chi) = \chi$.

The survey parameters outlined in Table I are adopted in order to emulate the performance of next-generation surveys currently in the early development phase, such as LSST[13], SNAP[14] and DUNE.

*Electronic address: frgs@ast.cam.ac.uk

TABLE I: Parameters adopted for the fiducial survey.

α	β	z_0	Area (deg ²)	\bar{n} (arcmin ⁻²)	σ_γ
2	2	1.13	20,000	100	0.2

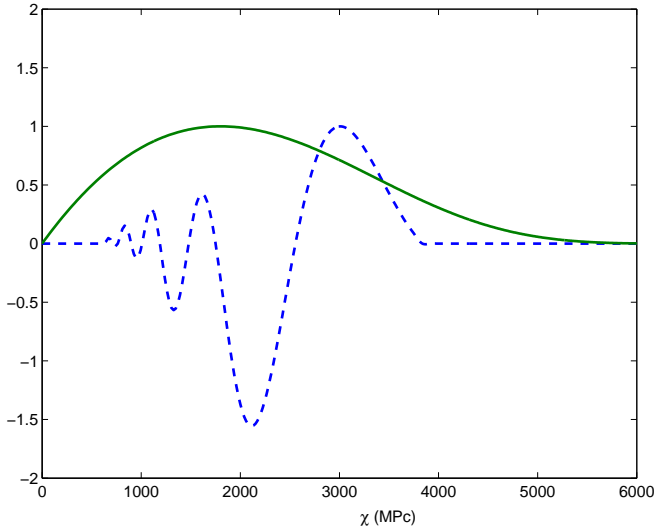


FIG. 1: This illustrates the difficulty of differentiating between a smooth and oscillatory power spectrum. The strength of the signal is approximately related to the integral of the product of the two lines. The solid line represents g , the lensing efficiency, whilst the dashed line is given by $P(k) - P(k)^{smooth}$ at $\ell = 150$.

Now consider the error of a given multipole. The standard formula for the error of an autocorrelation is given by Kaiser [7],

$$\sigma(\ell) = \sqrt{\frac{2}{(2\ell + 1)f_{sky}}} \left(C_\ell + \frac{\sigma_\gamma^2}{2n_g} \right), \quad (4)$$

where n_g denotes the number of galaxies per steradian within the bin, and f_{sky} is the fraction of sky covered by the survey. The rms prelensing ellipticity of sources is given by σ_γ .

Cosmological parameters are summarised in Table II. CAMB[15] is used to produce the matter power spectrum $P(k, z)$.

The challenge of distinguishing the “wiggles” becomes apparent when considering the plot of Fig. 1. Roughly speaking, the deviation produced by their presence is related to the integral of the product of the two lines. Thus if we could generate a similar oscillation in the (solid line), a significant improvement could be made. Fortunately, we do have some control over g .

TABLE II: The fiducial Λ CDM model.

Ω_m	σ_8	h	w	Ω_Λ	Ω_b
0.3	0.88	0.7	-1	0.7	0.0462

III. TOMOGRAPHY

By dividing the source galaxies into redshift bins, we generate different power spectra. The key to revealing the baryon oscillations from within the cosmic shear signal lies in comparing the correlations of galaxies which have their shear enhanced by the “wiggles” with those that are suppressed. The focus will be on angular scales corresponding to $100 \lesssim \ell \lesssim 300$, since these multipoles are lensed by the first few oscillations in the power spectrum.

As outlined in Eisenstein & Hu [8], the form of the oscillatory envelope in the power spectrum is well described by $j_0(k\tilde{s})$ where the Bessel function $j_0(x)$ is defined as $\sin x/x$, \tilde{s} is the effective sound horizon at the drag epoch, and for our purposes $k = \ell/\chi$ from (1). We therefore aim to generate a lensing efficiency g which can tune in to this signal, by careful selection of our redshift bins.

To reveal how the distribution $n(z)$ influences g , we differentiate (2) to find

$$\frac{d^3 g}{d\chi^3} = 2 \frac{dn(\chi)}{d\chi} + \frac{4n(\chi)}{\chi}. \quad (5)$$

By inspection, we anticipate a function of the form $n(\chi) = \sin(\tilde{s}\ell/\chi + \phi)$ could have the desired effect of producing a lensing efficiency which traces the oscillations in the power spectrum. Thus we split our population of galaxies into two intertwined bins.

$$n_A(\chi, \ell) = \begin{cases} n(\chi) & \epsilon(\chi, \ell) > 0 \\ 0 & \epsilon(\chi, \ell) < 0 \end{cases} \quad (6)$$

$$n_B(\chi, \ell) = \begin{cases} 0 & \epsilon(\chi, \ell) > 0 \\ -n(\chi) & \epsilon(\chi, \ell) < 0 \end{cases} \quad (7)$$

where $\epsilon(\chi, \ell) \equiv \sin(\tilde{s}\ell/\chi + \phi)$. This is the trial function, which we hope will divide the galaxy population into bins whose lensing kernels track the peaks and troughs of the baryon oscillations. The phase parameter ϕ is determined simply by exploring several values and selecting that which optimises the signal generated by lensing from the wiggles $P(k)^{wig} = P(k)^{fid} - P(k)^{smooth}$, i.e. the difference between a standard and smoothed power spectrum.

It is important to note that due to the ℓ -dependence of ϵ , the binning needs to be performed separately for each group of multipoles evaluated. Particular examples are illustrated in the top panels of Figs. 2 and 3. Here we have assumed a photometric redshift accuracy of $\Delta z \simeq 0.02$, simulated by convolving our distribution with a Gaussian. This can be seen as a smoothing of the bin edges.

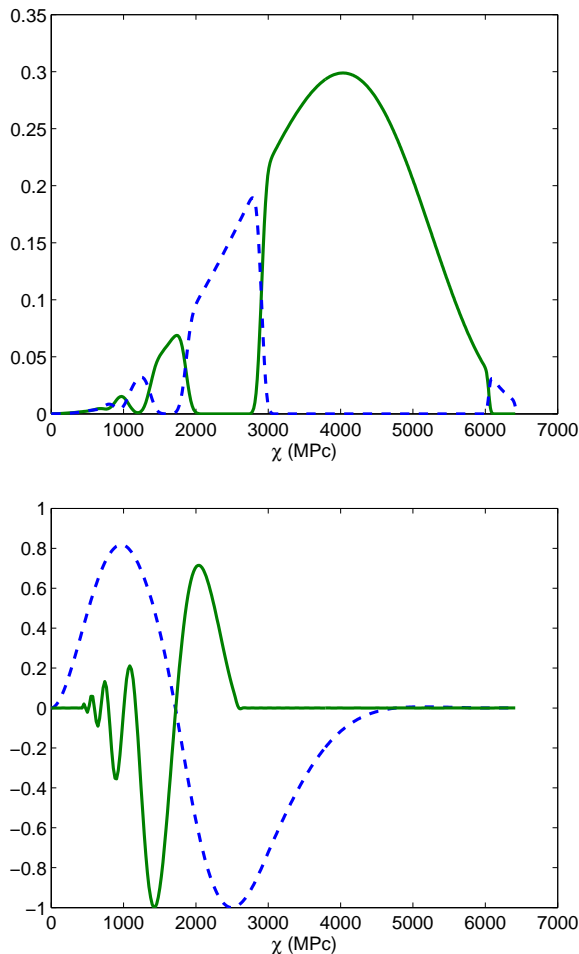


FIG. 2: $\ell = 100$ (Top) The solid and dashed lines represents the galaxy distribution for bins A and B respectively. The uneven allocation of galaxies is undesirable as it leads to a large sampling variance for bin B. (Bottom) The solid line is the difference between $P(\frac{\ell}{r}, \chi)$ and a smoothed version. The dashed line is the effective lensing efficiency, as defined in the text. In both diagrams, the vertical axes have arbitrary normalisation.

IV. BIN COMPARISON

We aim to devise a statistic which is sensitive to the oscillation, whilst remaining invariant to the overall height of the power spectrum. In doing so, this reduces the large cosmic variance error generated by the smooth component of the power spectrum. One problem we are faced with is that g , as defined in (2) and (3), is a smooth function and so oscillations in $P(\frac{\ell}{r}, \chi)$ are undetectable. We must therefore make use of the redshift bins as derived in the previous section.

Hu [9] found that the straightforward binning into high and low redshift galaxies still resulted in a high level of correlation. Here we use this to our advantage. The two intertwined bins share a great deal of structure and thus when subtracting their signals, the cosmic variance

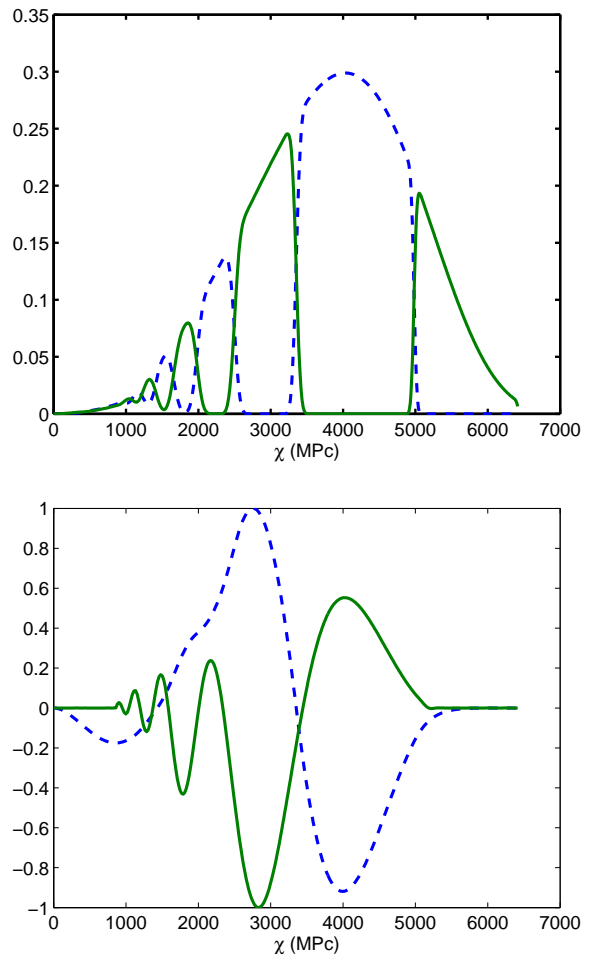


FIG. 3: The plots here are the same as in Fig. 2, but now $\ell = 200$.

contribution to the error is greatly reduced.

To begin, we define the statistic $F(\ell)$ in terms of the autocorrelations of the two bins from (6) and (7).

$$F(\ell) \equiv \Gamma C_{\ell}^{AA} - C_{\ell}^{BB} \quad (8)$$

where the scaling parameter Γ is given in terms of the fiducial cosmological model.

$$\Gamma = \tilde{C}_{\ell}^{BB} / \tilde{C}_{\ell}^{AA}. \quad (9)$$

From (1) and (8) we have

$$F(\ell) = \frac{9}{16} \left(\frac{H_0}{c} \right)^4 \Omega_m^2 \times \int_0^x \left[\frac{\Gamma g_A^2(\chi) - g_B^2(\chi)}{a^2 r^2(\chi)} \right] P\left(\frac{\ell}{r}, \chi\right) d\chi. \quad (10)$$

The important component of this equation is the *effective lensing efficiency*, given by $[\Gamma g_A^2(\chi) - g_B^2]$. In stark

contrast to the standard lensing efficiency from 1, this term can be seen to trace the baryonic oscillations in Figs. 2 and 3. The top plots demonstrate the ℓ -dependent binning, allowing the effective lensing efficiency to adapt to the changing position of the wiggles, as depicted in the bottom graphs.

V. ANALYSIS

There are a number of factors to consider when trying to maximise the signal-to-noise ratio generated by a change in the amplitude of oscillations. For example, uneven separation of galaxies into the two bins leads to an enhanced sampling variance. We also desire the production of an effective lensing efficiency which closely follows the oscillations. Thus we adopt a brute-force approach to evaluate the optimal phase ϕ for the binning function $\epsilon(\chi, \ell)$ discussed in the previous section. This was found to be well approximated by $\phi \simeq 0.26 - 0.0125\ell$.

Let us return to equation (4). Within the brackets, the two terms are attributed to cosmic variance and the sampling variance. The former tends to dominate at lower multipoles since the shear signal is greater.

For the full error expression of $F(\ell)$ we find

$$\sigma_F = \sqrt{\sigma_A^2 + \sigma_B^2 - 2r^2\sigma_A\sigma_B} \quad (11)$$

$$\sigma_A = \Gamma \sqrt{\frac{2}{(2\ell+1)f_{sky}}(C_\ell^{AA} + \frac{\sigma_\gamma^2}{2n_A})} \quad (12)$$

$$\sigma_B = \sqrt{\frac{2}{(2\ell+1)f_{sky}}(C_\ell^{BB} + \frac{\sigma_\gamma^2}{2n_B})} \quad (13)$$

$$\sigma_{AB} = \sqrt{\frac{2\Gamma}{(2\ell+1)f_{sky}}(C_\ell^{AB})}. \quad (14)$$

The correlation coefficient is given by

$$r^2 = \frac{\sigma_{AB}^2}{\sigma_A\sigma_B}, \quad (15)$$

where for brevity we have defined the terms $A \equiv \Gamma C_\ell^{AA}$ and $B \equiv C_\ell^{BB}$. The covariance between the terms A and B is denoted by σ_{AB}^2 . We typically find values of $r \sim 0.95$.

As an illustration, we use a power spectrum which has been smoothed by interpolating between the oscillations.

In order to quantify the constraint, we parameterise the amplitude of oscillations as O , such that $O = 1$ in the standard case, and $O = 0$ for the smoothed model. When marginalising over various cosmological parameters ($\Omega_m, n, w, h, \sigma_8$), we must be careful to include the effect of altering $n(\chi)$ since the bin selection must be made

in redshift space. Adopting a standard Fisher matrix approach, we find that the error does not significantly degrade from marginalisation, due to the unique functional form the signal imprints on $F(\ell)$. We have also investigated the variation of σ_F with cosmology, and tested higher redshift errors ($\Delta z \simeq 0.1$), and found these effects to be negligible. If the rms shear is increased by 50%, constraints degrade by $\sim 30\%$.

For our fiducial survey, without using tomography, the constraints on O are very poor, as expected from Fig. 1. We find $\sigma_O = 6$. However, by applying the approach outlined above, the smooth power spectrum can be ruled out at the 2σ level. We therefore anticipate that surveys at the level of the SKA [10], are required before significant results can be drawn.

VI. DISCUSSION

We have demonstrated how angular-dependent tomography can allow forthcoming cosmic shear surveys to detect oscillations in the matter power spectrum. Whilst this will never compete with high-redshift galaxy surveys, it does provide a unique consistency check. Cosmic shear and galaxy surveys probe the dark matter power spectrum via completely independent routes, and so such a complementary probe is welcome. It may also be of some assistance in controlling systematics.

It is likely that the errors derived here may be an *overestimate*, due to improvements which could be made with a more elaborate binning algorithm, and the lack of priors on cosmological parameters. Additionally, by weighting the galaxies (King & Schneider [11]) we could improve the extent to which g tracks the oscillations in the power spectrum, thereby enhancing the signal. However we anticipate that this gain may be tempered by the additional shot noise introduced, so its application could be limited to the lower multipoles where cosmic variance remains dominant.

The erosion of the baryonic features at small scales, by nonlinear structure, is not expected to affect our results since the signal is dominated by the strength of the first two oscillations.

“Precision cosmology” and a “concordance model” are oft-mentioned phrases, but perhaps a little premature [12]. The advent of cosmic shear surveys which cover a significant fraction of the sky is likely to deliver both.

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